

# DATA REDUCTION PIPELINE FOR THE MMT AND MAGELLAN INFRARED SPECTROGRAPH

IGOR CHILINGARIAN<sup>1,2</sup>, YURI BELETSKY<sup>3</sup>, SEAN MORAN<sup>1</sup>, WARREN BROWN<sup>1</sup>, BRIAN MCLEOD<sup>1</sup>, AND DANIEL FABRICANT<sup>1</sup>

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## ABSTRACT

We describe the new spectroscopic data reduction pipeline for the multi-object MMT/Magellan Infrared Spectrograph. The pipeline is implemented in IDL as a stand-alone package and is publicly available in both stable and development versions. We describe novel algorithms for sky subtraction and correction for telluric absorption. We demonstrate that our sky subtraction technique reaches the Poisson limit set by the photon statistics. Our telluric correction uses a hybrid approach by first computing a correction function from an observed stellar spectrum, and then differentially correcting it using a grid of atmosphere transmission models for the target airmass value. The pipeline provides a sufficient level of performance for real time reduction and thus enables data quality control during observations. We reduce an example dataset to demonstrate the high data reduction quality.

*Keywords:* techniques: spectroscopic, algorithms, data reduction, sky subtraction

## 1. INTRODUCTION AND MOTIVATION

The rapid progress in astronomical instrumentation and detector technology has resulted in a dramatic increase in the volume and complexity of astronomical data. Data reduction for modern wide-field mosaic imagers and multi-object spectrographs has become so computationally intensive and complex that individual astronomers can no longer easily process their own data. One response to this problem is dedicated data processing and analysis centers, such as TERAPIX (Bertin 2001). Another response is user-friendly, professionally maintained data reduction pipelines.

Multi-object spectroscopic observations are among the most difficult types of astronomical data to reduce and analyze. Slit mask spectrographs provide a high degree of flexibility in observing science targets over a large field of view, but produce datasets with very complex geometric properties that depend on slit configuration and optical distortions.

The MMT/Magellan Infrared Spectrograph (MMIRS) is a slit mask based cryogenic imaging spectrograph that can be used at the f/5 foci of the 6.5 m MMT or the Magellan Clay telescopes. Its optical and mechanical layouts, mode of operations, and control software are described in detail in McLeod et al. (2012). MMIRS operates in the imaging, longslit and multi-object spectroscopy (MOS) modes. The MOS mode is implemented by installing laser cut slit masks into the focal plane. Slit masks are designed and manufactured a few weeks prior to scheduled observations.

Spectroscopic data reduction of near-infrared ( $1.0 < \lambda < 2.5\mu\text{m}$ ) ground based observations is a non-trivial task that is significantly more challenging than optical data reduction. Standard general purpose software suites used in optical astronomy, such as NOAO IRAF, cannot be used as they do not take into account specific features of

the instrument or its near infrared detector.

Modern NIR detectors still stay about a decade behind optical CCDs in terms of read-out noise, dark current, and non-linearity of the response. Also, they all possess substantial color dependent variations in the pixel-to-pixel sensitivity reaching 40 per cent for HAWAII-2 detectors. An average number of unrecoverable hot or cold pixels is an order of several hundreds to tens of thousands on a single  $2048 \times 2048$  science grade NIR detector compared to dozens to a few hundreds on a modern optical CCD chip. Therefore, specific detector related calibrations are needed in the NIR and special techniques such as multiple or continuous detector read-outs are often used (Vacca et al. 2004).

Another family of difficulties arises from specific night sky properties in the NIR domain. Hydroxyl (*OH*) airglow lines dominating the NIR sky emission in the *H* and *K* bands are hundreds of times brighter than optical *OH* lines in the *I* band. They also possess high variations in time (minutes) and space (degrees on the sky). The NIR water vapor telluric absorption bands cause 100 per cent absorption (i.e. are completely opaque) at some wavelengths and absorb tens of per cent of the light over extended wavelength intervals. Therefore, the sky subtraction and telluric correction become the most difficult steps of the NIR data reduction. Approximate techniques can work well in the optical domain and produce reasonable results, however, in the NIR where all features are orders of magnitude stronger, and emission airglow lines are much more numerous, a different approaches to both observational strategy and data reduction are needed.

The “classical” optical sky subtraction, when the sky spectrum is created by averaging “empty” regions of the slit below and above the target after linearizing and rectifying a spectral frame and then subtracted at every slit position, leads to significant artefacts, if applied to NIR data, making further data analysis impossible. The advanced sky subtraction technique by Kelson (2003) operates on non-reampled frames and provides nearly Poisson limited sky subtraction quality for optical longslit spectra. However, because of flat field imperfections

igor.chilingarian@cfa.harvard.edu

<sup>1</sup> Smithsonian Astrophysical Observatory, 60 Garden St. MS09, Cambridge, MA 02138 USA

<sup>2</sup> Sternberg Astronomical Institute, Moscow State University, 13 Universitetski prospect, Moscow, 119992, Russia

<sup>3</sup> Las Campanas Observatory, Carnegie Institution of Washington, Colina el Pino, Casilla 601 La Serena, Chile

and color dependent pixel-to-pixel sensitivity variations in NIR detectors, this technique does not provide the desired sky subtraction quality. Another obstacle specific to multi-slit datasets is the short length of each individual slit that affects sky model quality in the Kelson (2003) algorithm.

At present, there are several existing data reduction solutions for optical multi-object spectrographs using slit masks. The Gemini Multi-Object Spectrograph data reduction software is an IRAF based package distributed by the Gemini observatory<sup>4</sup>. It implements basic data reduction techniques used in optical spectroscopy and a “classical” sky subtraction. Another two software solutions which implement the Kelson (2003) sky subtraction technique are: a stand-alone COSMOS package developed and distributed by Carnegie Observatories<sup>5</sup> that is used for as a data reduction solution for the IMACS spectrograph operated at the 6.5-m Magellan telescope, and a Keck DEIMOS data reduction pipeline (Newman et al. 2013), an IDL package based on the data reduction suite from the Sloan Digital Sky Survey project SPEC2D. There is also the SPARK package (Davies et al. 2013) for the data reduction from the KMOS multiple integral field unit NIR spectrograph operated at the European Southern Observatory Very Large Telescope. However, this instrument has a fixed geometry and the specific observational strategy is used, therefore the pipeline cannot easily be modified to reduce slit mask data.

Our goal is to design and implement an efficient and flexible system to reduce multi-slit and longslit spectroscopic data collected with MMIRS. Our intention is make this a stand-alone package relying as little as possible on third-party software. The pipeline should be easy to install and use by users not connected to the instrument team and also provide a sufficient level of performance for real time reduction to enable data quality control during observations.

Our approach is to control the pipeline with text files having the FITS-header like format, i.e. keyword–value pairs, easy to create and edit and similar to NOAO IRAF packages. We pay special attention to the quality of sky subtraction, as it is perhaps the single most important step required for the successful analysis and interpretation of near-infrared (NIR) datasets. We also develop a technique for the telluric correction of NIR spectra. Our approach requires only one telluric star observation and then computes differential corrections based on a grid of pre-computed atmosphere transmission models.

Data reduction for MOS and long-slit data in the optical and NIR share common algorithms for some reduction steps. The overall layout of a NIR spectral pipeline for MOS data resembles that of pipelines for optical MOS and integral-field unit (IFU) spectrographs. Here we partially adopt the structure of the data reduction package for the Multi-Pupil Fiber Spectrograph (MPFS, Afanasiev et al. 2001) at the Russian 6-m telescope described in Chilingarian et al. (2007). This data reduction package was later transformed into a universal data reduction pipeline for integral-field unit (IFU) spectrographs and then used to reduce data from ESO VIMOS

(Chilingarian et al. 2009), Calar-Alto PMAS (Chilingarian & Bergond 2010), and Gemini GMOS-IFU. Some blocks of the code in the current MMIRS data reduction pipeline (e.g. certain diagnostic plotting routines, the quality assessment for the wavelength calibration) and the task control file structure are based on ideas from that IFU data reduction package.

The paper is organized as follows. In Section 2 we briefly present current MMIRS capabilities including the upgrade made in 2014. In Section 3 we describe the format of raw data produced by the MMIRS data acquisition software and describe the observing protocols for spectroscopic observations. In Section 4 we describe the data reduction pipeline, specific algorithms we developed and implemented, the output data format. In Section 5 we discuss the quality of the sky subtraction that we achieve using the pipeline. We summarize in Section 6. The appendices describe associated calibration datasets, provide a list of third-party routines used in the pipeline code, and give an example of the pipeline control file.

## 2. MMIRS CAPABILITIES

MMIRS is capable of slit-mask multi-object spectroscopy over a  $4 \times 6.9$  arcmin field, long-slit spectroscopy over a 6.9 arcmin slit, and direct imaging in the  $Y$ ,  $J$ ,  $H$ ,  $K$  bands. A set of grisms provides low- to intermediate-spectral resolution ( $R = 1100 \dots 3000$ ) spectroscopy, and are used in a combination with bandpass selection filters ( $zJ$ ,  $HK$ , and  $Kspec$  for the  $J$ ,  $HK$ , and  $K3000$  grisms respectively) or a standard  $H$ -band filter for the  $H3000$  grisms (see Fig. 1). McLeod et al. (2012) provide a detailed description of the MMIRS spectral and imaging capabilities, here we outline the updates since 2012.

In the fall of 2014 we performed a number of upgrades in the spectrograph, first available to observers during the 2014B run on the 6.5-m Magellan Clay telescope.

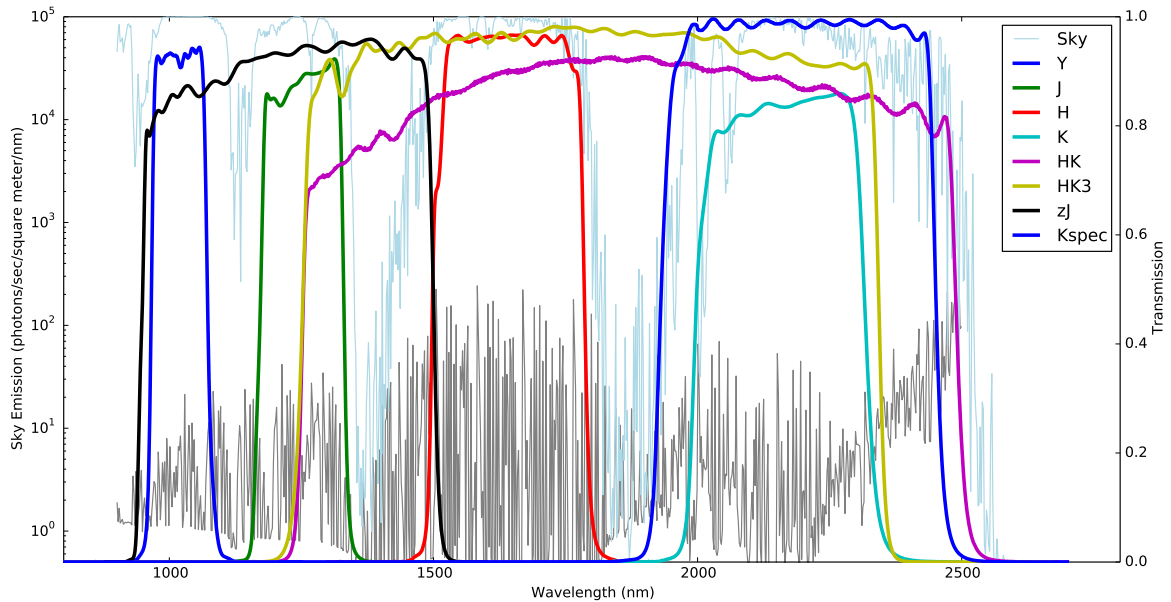
- We replaced the HAWAII2 detector with HAWAII2-RG. The new detector provides 10 times lower dark current, increased sensitivity at shorter wavelength (0.8–1.3  $\mu\text{m}$ ), lower read-noise level (11  $e^-$ ), and much lower pixel-to-pixel sensitivity variations. The array is read through 32 amplifiers in 1.475 sec.
- We installed two new virtual phase holographic grisms,  $H3000$  and  $K3000$ , that provide  $R \approx 3000$  spectral resolution  $R \approx 3000$  in the  $H$  and  $K$  bands, respectively.
- We installed a new  $HK$  spectral bandpass filter called  $HK3$ . Compared to the old  $HK$  filter, the new  $HK3$  filter has higher overall throughput and a shorter wavelength cut-off at 2.33  $\mu\text{m}$  that reduces by a factor of 4 the scattered light originating from the thermal glow of the gate valve.
- We installed the  $Kspec$  high throughput bandpass filter, with a cut-off at 2.45  $\mu\text{m}$  designed specifically for  $K$ -band spectroscopy with the newly installed  $K3000$  holographic grism.

## 3. MMIRS DATA FORMAT AND OBSERVING PROTOCOL

### 3.1. Raw data format

<sup>4</sup> <http://www.gemini.edu/sciops/data-and-results/processing-software>

<sup>5</sup> <http://code.obs.carnegiescience.edu/cosmos>



**Figure 1.** Transmission curves of filters available in MMIRS as of October 2014 are shown over the throughput spectrum of the earth atmosphere (light blue) and the airglow emission spectrum (grey).

MMIRS is equipped with a HAWAII-2RG (formerly, HAWAII-2) detector that is read non-destructively “up-the-ramp” via 32 amplifier channels at a cadence set by the observer, typically once every 1 or 5 seconds depending on the exposure time. Every read-out is stored as a two-dimensional image extension in a FITS file. The last read-out is put into the first image extension in order to facilitate the computation of double correlated frames for quick-look purposes by subtracting the two first consequent extensions from each other. The final multi-extension FITS files are stored in the MMIRS raw data archive and used as the input product for the data reduction pipeline.

It is important to notice that the multi-extension FITS data format is the same for every type of MMIRS observing mode: imaging, long-slit or multi-object spectroscopy. However, MOS raw data also contain an additional text file describing the slit mask layout (mask definition file hereafter).

The first step of the data reduction process is thus, for each pixel, to fit a smooth monotonic function to the values obtained in that pixel at every read-out (see Fig. 2). This approach, usually referred to as “up-the-ramp fitting” offers a number of advantages over a standard double correlated frame, that is a difference between the first and final read-outs. Up-the-ramp fitting (a) reduces the read noise because the same pixel is read multiple times; (b) takes into account the detector non-linear response; (c) recovers fluxes from pixels saturated in the middle of an exposure after a few read-outs; and (d) recovers fluxes from pixels affected by cosmic ray hits in the middle of exposure.

In the current implementation of the MMIRS data reduction pipeline, we perform the non-linearity correction using pre-computed polynomial approximations to the non-linear detector response derived from calibration data. This approach allows us to obtain fluxes using a

linear function in the up-the-ramp fitting procedure.

### 3.2. Spectroscopic observing protocol

To assure that spectral data collected with MMIRS can be reduced by our pipeline, observers should use the following observing protocol.

The pipeline works on pairs of spectra spatially dithered along the slit taken one after another. Therefore, observer should use a *dithering pattern* with an even number of positions chosen in such a way that the distance between positions in every pair stays constant. The distance must be a multiple of 0.2 arcsec (one pixel on the detector) and should be at least 3 times as large as the image quality FWHM to avoid contamination of spectra on difference frames by their dithering counterparts. The recommended dithering pattern for 6 arcsec long slits, the most commonly used slit length in MOS masks, is  $+1.6 -1.2$ ,  $+1.2 -1.6$  arcsec. For longslit observations, this pattern depends on the spatial extent of an observed source and may be as wide as  $\pm 120$  arcsec for large galaxies and nebulae.

We strongly recommend taking *night time calibrations* because the wheel positioning inside the spectrograph is not 100 per cent repeatable. Observers should acquire spectral flat fields, therefore, before any action that requires moving a grism or a slit or MOS mask (e.g. checking the slit or MOS mask alignment). For faint targets and long exposure times (180sec or longer), we use airglow *OH* lines for the wavelength calibration (see below), however, we still recommend to take arc frames (*Ar*) as a part of the calibration plan after taking flat fields. This takes less than a minute and will provide a backup option if the wavelength calibration using *OH* lines fails.

We recommend checking the *slit or MOS mask alignment* by removing the grism and taking a slit image every couple of hours.

We recommend observing *telluric standard stars* in or-

der to remove the atmospheric absorption pattern from spectra and perform relative flux calibration (see below). We strongly recommend using only *A0V* stars. The current algorithm in the MMIRS pipeline uses one telluric standard observation and scales it to the airmass of an observation using atmosphere transmission models. However, it does not take into account possible changes in the water vapor level. Therefore, we recommend observing a telluric standard at least once per field, and no less than 3 times per night if one field is observed the whole night. If a large airmass range is covered during the observation of one field, we recommend observing the telluric standard around the lowest and the highest airmass, so that there will be a choice during the data reduction. In the MOS mode, we recommend observing a telluric standard through 5 slits, central, top, bottom, left, and right, in order to achieve the complete wavelength coverage and high signal-to-noise ratios. Telluric standards should be chosen to be faint enough to avoid saturation, but bright enough to achieve peak counts of several to twenty thousands in every individual spectrum. For the longslit mode, a telluric standard is observed using the same procedure as a science target with a dithering including two positions, for example +10 and -10 arcsec.

The *mask design* must comply with the following guidelines: (1) all science target slits should have equal widths, because the sky subtraction technique relies on this assumption; (2) alignment star boxes should have similar slit lengths to the science target slits, because the pipeline uses the alignment star spectra as references when co-adding individual observations. If the alignment stars are dithered out of their boxes, the co-adding procedure will fail and instead assume that the objects are perfectly centered in their slits, assuming the commanded offsets.

#### 4. DATA REDUCTION PIPELINE

The MMIRS data reduction pipeline is a stand-alone package implemented in IDL. It can be used to reduce both long-slit and multi-object spectroscopic MMIRS observations in a fully automatic way. Some of the pipeline blocks may be used to reduce imaging data as well. With minor modifications, the pipeline can be used to reduce data from other optical and NIR multi-object spectrographs.

The MMIRS data reduction pipeline is distributed under the GPL license. A stable version of the pipeline code (currently v. 1.0) is distributed as an archive from the web-site of the Telescope Data Center<sup>6</sup>. The current development version of the code is available from the public GIT repository at BITBUCKET<sup>7</sup>. The MMIRS pipeline depends on the ASTROLIB package distributed by the NASA Goddard Space Flight Center.

The pipeline is controlled by a task control file having a format similar to FITS headers, i.e. a set of keyword - value pairs where the keyword length is limited to 8 characters and the total line length is limited to 80 characters. This file can be created either in a text editor, or generated by an automated system that parses observing

**Table 1**  
Grisms and filter combinations available as of October 2014 and their support status in the MMIRS pipeline v 1.0.

Grism	Filter	Sp.Res ( <i>R</i> )	$\lambda$ , $\mu\text{m}$	Supported
<i>J</i>	<i>J</i>	2200	1.15 – 1.35	yes
<i>J</i>	<i>zJ</i>	2200	0.95 – 1.50	yes
<i>H</i>	<i>H</i>	2300	1.50 – 1.80	yes
<i>H</i>	<i>HK</i>	2300	1.25 – 2.15	yes
<i>HK</i>	<i>HK/HK3</i>	1200	1.25 – 2.45	yes
<i>H3000</i>	<i>H</i>	3000	1.50 – 1.80	planned
<i>K3000</i>	<i>Kspec</i>	3000	1.90 – 2.45	planned
<i>HK</i>	<i>zJ</i>	2400	0.95 – 1.50	no
<i>HK</i>	<i>Y</i>	3000	0.95 – 1.10	no

logs, and then modified if necessary.

This file can be edited in order to perform a specific data reduction step, but by default the data are reduced completely until the sky subtraction step. We adopted the task control file approach from the IFU data reduction package mentioned earlier.

At present, all of the metadata associated with existing MMIRS observations are stored in a relational database using PostgreSQL database management system. We have a script implemented in PERL that performs searches in this database based on object coordinates or name. This script then finds the best suitable calibration frames including telluric standard stars. Finally, the script generates pipeline task control files for the entire observing sequence of a given target, which may include hundreds of frames. Each such file normally includes information for two spatially dithered exposures.

The pipeline supports long-slit and multi-object spectroscopic observations through 1 to 12 pixels (0.2 to 2.4 arcsec) wide slits/slitlets. We list the grism and filter combinations currently supported by the pipeline in Table 1.

##### 4.1. Primary data reduction

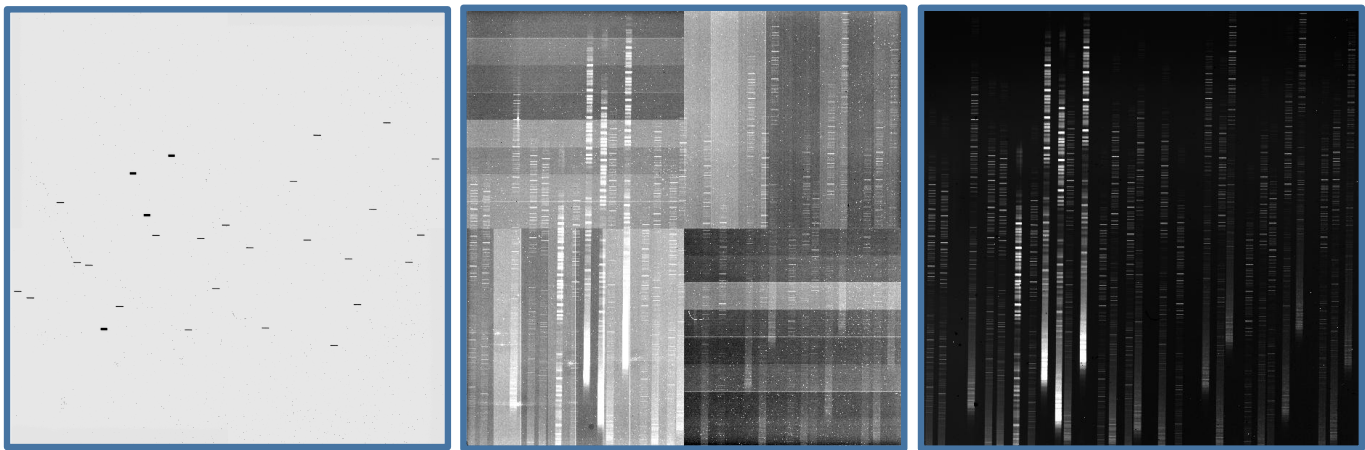
The primary data reduction includes the following two steps (see Fig. 2):

- *Applying the non-linearity correction and fitting the up-the-ramp slope* in every pixel. The result of this step is a two-dimensional image. We perform the non-linearity correction using a set of pre-computed polynomial functions (7th to 9th orders) available as a part of the MMIRS pipeline calibration data package, see below. At this stage, any unrecoverable saturated pixels are also masked out. The counts, corrected for the non-linear detector response, are then fit with a linear function. The slope of the line is the flux rate in that pixel. Because this step is computationally intensive, and because the code does not require any input parameters, it is executed only when a dataset is reduced for the first time. Unlike further steps of the data reduction which are repeated as needed, the code checks for the presence of pre-processed 2D frames to avoid repeating this step. If it is necessary to re-run this data reduction step, the pre-processed 2D frames should be deleted from the input directory.

- *Dark subtraction* is the next step, and it is done

<sup>6</sup> [http://tdc-www.harvard.edu/software/mmirs\\_pipeline.html](http://tdc-www.harvard.edu/software/mmirs_pipeline.html)

<sup>7</sup> [https://bitbucket.org/chil\\_sai/mmirs-pipeline](https://bitbucket.org/chil_sai/mmirs-pipeline)



**Figure 2.** A slit mask image (left panel), a raw readout of its spectrum from the HAWAII-2 detector (central panel) and the result of the up-the-ramp fitting and dark subtraction (right panel). Individual spectra are dispersed in the vertical direction. Four alignment star boxes visible as “bold” slits on the left panel correspond to four brighter spectra in the left part of the central and right panels.

to the up-the-ramp processed 2D frames. We average several dark frames and subtract them from science and calibration frames. Dark frames are obtained after a night of observations by a dark script for every up-the-ramp cadence and exposure time combination. Since we use different up-the-ramp cadence and exposure time settings for different types of data, we use different dark frames for processing science exposures, flat fields, comparison spectra and telluric standards.

These steps are detector specific and they rely on the calibration data distributed with the pipeline code: non-linearity correcting polynomials and saturation limits. They can be used for a different detector, once corresponding calibration datasets have been updated. In Fig 2 we provide an example of a raw read-out from the MMIRS detector and the result of the primary data reduction applied to the same dataset.

#### 4.2. Spectral tracing, flat fielding, and wavelength calibration

After the primary data reduction is complete, we subtract pairs of dithered spectral exposures (difference spectra hereafter) and process them through the rest of the pipeline steps. Individual exposures need to be processed in order to derive flux uncertainties, done by propagating the initial photon statistics through to the final data products.

The following data reduction steps are typical for any slit mask spectrograph. We provide our own implementations of all algorithmic blocks with as few dependencies on external IDL packages as possible. These solutions can be used in the data reduction pipeline for any optical or NIR spectrograph with only minor modifications.

Long-slit spectra are reduced as a degenerated case of MOS fields with only one “target” slit and no “alignment star” slits. At this stage we generate a mock mask definition file for a long-slit setup using the same format as that for real MOS masks. This allows us to use the same code and the same data reduction approach for all types of MMIRS spectral data.

- *Spectral tracing* is a mandatory first step of the MOS data reduction. The pipeline reads the MOS

mask definition file, then uses it to trace the two-dimensional spectra, and the gaps between them, on a spectral flat field exposure. This information is stored in a table and used in the subsequent steps of the data reduction.

- *Diffuse light modelling and subtraction* is a step that can be optionally performed for MOS observations. It is also skipped when dealing with difference spectra, because the diffuse light component is effectively cancelled by subtracting individual frames. Using the spectral tracing results, we measure count levels in the gaps between slit images in science exposures, telluric standards, and calibration frames. Then, a smooth background model is constructed from those measurements using low-order polynomials along the dispersion direction, and basic splines (*b-splines* hereafter) across the dispersion direction. This approach models the diffuse background, but it cannot handle ghost spectra originating from reflections off the back surface of the mask. The amplitude of ghost spectra is about 1 per cent of the flux, however, and so they do not seriously affect the rest of the reduction process unless very bright sources are observed or used as alignment stars.
- *Mapping the optical distortions* is a step performed using the results of the flat field tracing. We use a low order 2D polynomial approximation to describe distortions originating from both the collimator and camera optics, sufficient to provide us with a sub-pixel precision at the end. The distortion map accounts for the imperfect positioning of the grism, which causes spectra to be not exactly parallel to the detector edge (0.2 to 0.7 deg for the current grism setups), and also for the subtle variation of the spatial scale along the wavelength direction. The distortion maps turn out to be very stable in time and do not differ significantly from one mask to another. Therefore we store a template version of the distortion map for every grism, and compare the derived distortion map against the appropriate template during the data reduction. If the distortion maps differ significantly,

which may happen in case of non-uniform filling of the MOS mask by slits, we use the values from the template version. Hardware maintenance on MMIRS optical and mechanical elements in April of 2014 caused the rotation angle of the *HK* grism to change slightly. In order to handle this, we keep two versions of the *HK* grism calibration, and the pipeline decides which one to use based on the date of observations stored in the FITS header.

- *Extraction of two-dimensional spectra* is done after tracing and distortion mapping. The pipeline reads the MOS mask definition files and extracts 2D sub-frames corresponding to bounding boxes of individual spectra from the original frames with no resampling. This operation is performed on both individual exposures and subtracted pairs. If one of the neighboring spectra enters the bounding box, it is masked out.
- *Flat fielding* is a very important part of the data reduction procedure because pixel-to-pixel sensitivity variations in the HAWAII-2 detector reach 35 per cent and they are dependent on the spectral content of the light. It is also required to handle flux variations along slits due to the imperfect mask cutting (or similar defects on long slits permanently installed in the spectrograph). We normalise flux to unity using the  $5 \times 5$  median-averaged frame as a reference in order to exclude possible cosmic ray hit or hot pixel residuals. For MOS data there are two options: (a) normalisation to the maximal flux in one of the slits and (b) per-slit normalisation. The internal flat field lamp provides imperfect illumination of the detector plane, therefore we recommend using the per-slit normalisation.
- *The wavelength calibration* is done slightly differently for long-slit and MOS modes. Depending on the exposure time and the brightness of the science target (controlled by the BRIGHT keyword in the pipeline control file) we use either internal argon arc lamp or atmosphere airglow *OH* lines to construct the wavelength solution. By default, the internal *Ar* lamp is used only in case of short exposures, when the number of well-exposed airglow lines is insufficient to achieve the desired quality of the wavelength solution (1/20 of a pixel or better). Also, the wavelength solution computation procedure will use internal arc frames if the *OH* based computation fails for any reasons. However, a pipeline user can force using internal arcs or *OH* lines with the corresponding setting in the pipeline control file. The pipeline calibration data package includes two separate line lists (*Ar* and *OH*) which contain vacuum wavelengths, relative intensities of different lines, and a priority flag (0 to 3) for the line usage with “3” being the highest priority and “0” for the lines to ignore in the wavelength solution.

A model *Ar* or *OH* spectrum is constructed using the information from the line list and the initial approximation of the wavelength solution derived once for every grism and stored in one of the

pipeline routines. Then, an observed spectrum is compared to the model and emission lines are automatically identified using an iterative procedure with outlier removal. This procedure includes a piecewise cross-correlation to find an initial shift between a spectrum and a model, then it searches for emission lines and identifies them against the line list. Finally, the initial wavelength solution is approximated using a two-dimensional polynomial (2nd or 3rd order in both directions, along and across dispersion).

This step is applied to the entire frame in the long-slit mode, or to every extracted slit in the MOS mode. Alignment star boxes are not processed at this stage because the spectral lines are too broad and many of them are blended.

The second step of the wavelength calibration is applied to MOS data only: we approximate the behaviour of polynomial coefficients in all slits simultaneously as smooth two-dimensional polynomial functions of the  $(X, Y)$  slit position in the mask. This allows us to handle alignment star boxes by simply evaluating the resulting polynomials in the corresponding positions on the mask. This will produce a useable wavelength solution if the masks were cut perfectly. However, since slits always contain some imperfections on their edges, we need to perform a final adjustment of the wavelength solution at every position in every slit.

The last step, which is also applied to long-slit data, creates a “template spectrum” using a science frame assuming that all targets are faint and airglow lines are prominent and bright (which is true in over 90 per cent of cases). The “template spectrum” is created from spectra resampled in wavelength using the preliminary wavelength solution and taken close to the center of the frame. Then the spectra at every position across dispersion are cross-correlated against the template spectrum and the zero point of the wavelength solution is adjusted corresponding to the position of the correlation peak. This approach may fail if targets are bright. In this case, the same procedure can be performed on the internal arc spectrum, however it will not assess possible systematic offsets of the wavelength solution which may arise from the optical system not being ideally telecentric.

#### 4.3. Sky subtraction

Reliable and precise subtraction of night sky emission is one of the most critical steps in NIR data reduction. NIR night sky spectrum contains very bright emission lines (mostly hydroxyl, *OH*) as well as a continuum background that change in time and across the field of view. Faint targets observed with MMIRS with integration times of many hours are often hundreds of times fainter than the NIR night sky level.

In the MMIRS pipeline we use a hybrid approach to subtract the sky emission using a combination of classical and recently developed techniques. As mentioned above, we create difference images that we process through the pipeline, which is a classical approach to sky subtraction in NIR.



However, difference spectra usually exhibit residual night sky emission originating from the short-term time variations of OH lines on a timescale of minutes. For the typical 300–600 sec duration of science exposures, these variations may reach a few per cent (sometimes tens of per cent), therefore it is important to tackle the line residuals which can be positive or negative.

We use the sky subtraction technique proposed by Kelson (2003) which we modified for our multi-slit spectroscopic data. The main idea of this sky subtraction technique is to use non-resampled spectral frames and precise pixel-to-wavelength mapping in order to create an over-sampled model of the night sky spectrum. This over-sampled night sky spectrum is then parametrized using  $b$ -splines and evaluated at every position at every slit. Using this approach effectively eliminates artefacts originating from the interpolation of extremely sharp and undersampled emission line profiles of airglow OH lines.

However, the Kelson sky subtraction approach requires significant curvature of slit images on the detector frame in order to properly oversample the night sky emission lines. While this is true for the long-slit spectroscopic mode of MMIRS, where the curvature exceeds 10 pixels along the slit length, in the MOS mode the situation is very different. For a typical slit length of 7–8 arcsec, the curvature is close to zero in the central slit images and only 1 or 2 pixels at the edges of the field of view. Therefore, we cannot use the standard Kelson (2003) technique in the MOS mode.

We modify the Kelson algorithm by adding an extra dimension to the sky spectrum parametrization: the published approach uses the pixel position along the slit as an extra parameter, while we use 2-dimensional physical positions of every pixel on the slit mask. This allows us to take into account the residual flat fielding errors, both along the dispersion direction and across the field of view.

After the wavelength calibration step, we have a mapping between the pixel location on the detector plane and its position in the slit mask and wavelength:  $(X_{\text{pix}}, Y_{\text{pix}}) = D(X_{\lambda, \text{mask}}, Y_{\text{mask}})$ . This mapping allows us to take the flux from every detector pixel on flat fielded frames inside the traces of the science target slits (they are assumed to be equally wide), masking the regions where science targets are expected to land in the corresponding slits, to obtain a dense irregular sampling of the  $(\lambda, X_{\text{mask}}, Y_{\text{mask}})$  coordinate space by the sky flux. The sky flux in this parameter space is expected to change rapidly as a function of wavelength on a scale of the spectral resolution (i.e. a few Å in the case of MMIRS) and slowly as a function of the mask position, because this change is due to large scale flat fielding uncertainties and spatial variations of the airglow emission. Hence, the night sky emission can be parametrized by a smoothing spline (e.g.  $b$ -spline) in the wavelength direction having about 700 nodes with the coefficients slowly varying as functions of  $X_{\text{mask}}$  and  $Y_{\text{mask}}$ , e.g. represented by the 3rd order Legendre polynomials in two dimensions. The number of coefficients of the parametrization to be evaluated will be on the order of 10000–20000 depending on the chosen number of nodes and degrees of the Legendre polynomials.

For a typical situation of a well designed slit mask, the

spectral traces occupy about 75% of the detector area that is about  $3 \times 10^6$  pixels. If we exclude the expected traces of unresolved science targets, this number will decrease to about  $2 \times 10^6$  pixels, that still provides a factor of 100–200 redundancy for the reliable computation of the  $b$ -spline parametrization with the iterative outlier rejection.

We use the publicly available code for the  $b$ -spline computation from the SDSS IDLUTILS package, and modify the routines in order to fit the additional dimension with Legendre polynomials. The modified routines are included in the pipeline distribution along with the original two-dimensional  $b$ -spline fitting code.

The night sky modelling and evaluation is the longest step in the data reduction, and it may take up-to a minute of single core CPU time on a modern PC (3 GHz CPU).

Remarkably, our sky subtraction applied to difference frames reaches the Poisson photon noise limits, as we demonstrate below.

#### 4.4. Final cosmic ray cleaning and linearisation

After completing the sky subtraction on non-resampled data, we perform cosmic ray and hot pixel cleaning using the modified Laplacian filtering technique (van Dokkum 2001) on difference images. We modify the original code so that it can handle both negative and positive “hits” on images because we are dealing with difference images.

Next, we linearize the spectra in wavelength, and rectify them (i.e. take out the geometric distortions from slit imaging) using the distortion map and wavelength solutions derived at previous steps.

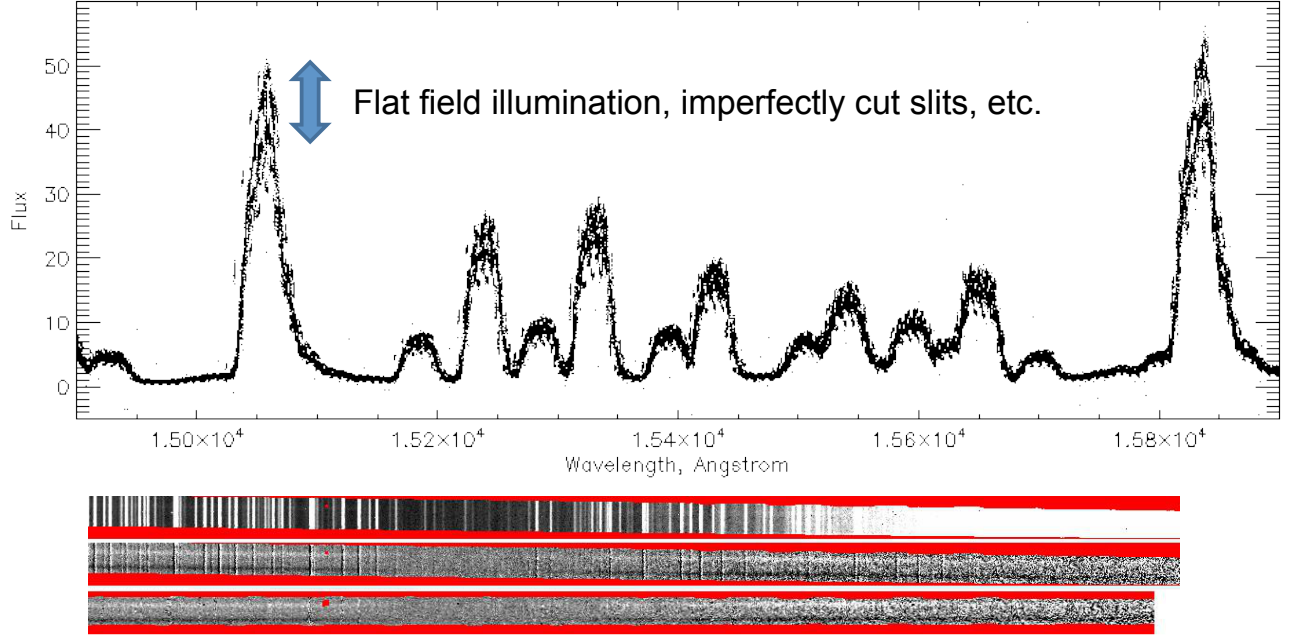
#### 4.5. Telluric correction

Correction for telluric absorption is another important step of NIR data reduction. Beside OH emission lines, there are strong water vapor absorption bands located all over the NIR domain which vary as a function of water vapor and airmass at the time of observation. These bands are responsible for nearly complete absorption of light between boundaries of  $J$  and  $H$ , and  $H$  and  $K$  photometric bands. Even between these regions of complete absorption, there are features reaching 15 per cent absorption which may look like spectral lines/bands in the target spectra if left uncorrected.

In order to correct for the telluric absorption (Vacca et al. 2003), we observe telluric standard stars which are typically A0V stars whose spectra contain very few intrinsic features and can be relatively well modelled. We then derive the transmission curve by comparing the observed spectrum to the model predictions.

It is worth mentioning that the transmission curve will also include the spectral response function of the detector, and therefore, the telluric correction automatically performs a relative flux calibration of the data.

The standard approach is to observe telluric standard stars at different airmasses (usually airmass values bracketing a science observation), which allows one to compute the approximate correction of telluric absorption bands by interpolating the correction functions. In the regions of intermediate and very strong absorption, however, certain absorption lines get to full saturation and therefore the response cannot be interpolated using only two observations at minimal and maximal airmasses. Hence, it

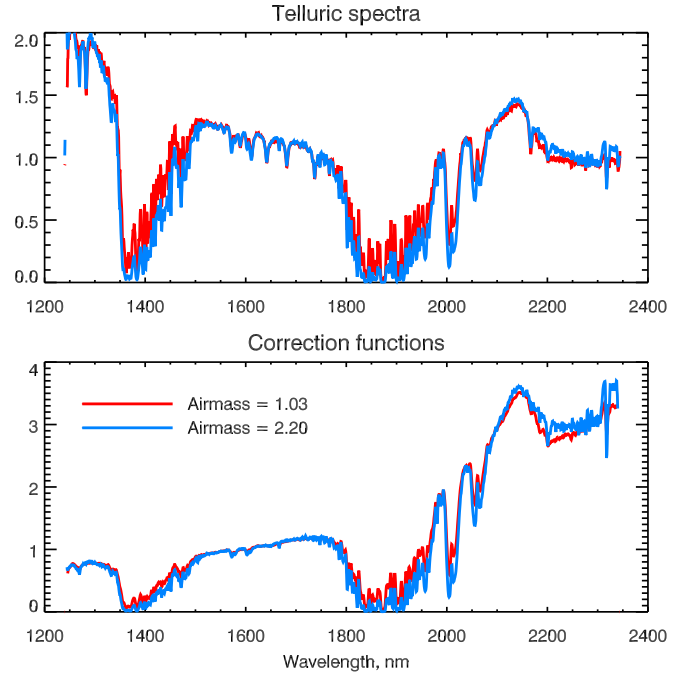


**Figure 3.** An example of the sky subtraction process in the MMIRS data reduction pipeline. The top panel displays the oversampled night sky vector computed from the original spectrum (it is better than a difference spectrum for illustrative purposes only), where the variance of counts at every wavelength originates from the imperfect flat field illumination and/or imperfectly cut slitlets in the mask. It is taken into account by introducing smooth variations of the sky model in two dimensions across the field of view (see the text). The bottom panel shows three extracted 2D spectra from a MOS dataset: (a) an original spectrum; (b) a difference spectrum with notable residuals of sky lines with clearly visible positive and negative traces of a science target; (c) the same difference spectrum after the sky subtraction using the modified Kelson technique.

is impossible to get reliable correction in these spectral regions. It is, however, rarely required by science programmes because the efficiency of observations in highly absorbed regions is very low. At the same time, in the regions of intermediate absorption, this standard approach can lead to significant artefacts.

An alternative solution is to use a grid of numerical models of the atmosphere transmission, and match them against an observed spectrum (Kausch et al. 2014) assuming that it is featureless. This approach will result in artefacts if the observed target has spectral features where an observed science spectrum is fit against the models. It is also very problematic to correct very faint spectra where no significant continuum flux presents. The latter issue makes it impossible to use the fully model-based approach to correct NIR observations of distant galaxies where only a few emission lines are detected in a spectrum after hours of observations.

In the MMIRS pipeline we propose a hybrid approach. We use one observation of a telluric standard star at an airmass close to that of the science observation, and compute the empirical atmosphere transmission function by taking the ratio of the observed telluric spectrum and a synthetic stellar atmosphere of that star. This transmission function is then fit against a grid of pre-computed theoretical models of NIR atmospheric transmission for a given airmass, and convolved with the MMIRS instrumental line-spread function. From this fit we derive the best-fitting value of water vapor. Then, we take a grid of atmospheric transmission models at different airmass values for that value of water vapor, and apply a differential multiplicative correction to the empirical trans-



**Figure 4.** An example of two spectra of a telluric standard star having the A0V spectral type obtained at different airmasses (top panel) and the derived multiplicative correcting functions (bottom panel).

mission function computed at the first step to account for the airmass difference between the observations of the telluric standard and the science target. A transmission function is derived in this fashion for every science



exposure and then applied to sky subtracted linearized spectra.

Another important aspect of the telluric correction is related to handling different slit widths. To compute the transmission function one needs to transform the spectrum of a high-resolution model of a A0V star into one comparable to the observed spectrum. This transformation depends on the relation between the atmosphere seeing quality and the slit width. We use the following convention: if the atmosphere seeing quality derived from the Gaussian FWHM of the telluric star spectrum is better than the slit width, then we use the empirically obtained slit profile (a Gaussian with FWHM=2 pix convolved with the  $\Pi$ -shaped profile) to convolve the model; alternatively, if the seeing quality is worse than the slit width, we use a simple Gaussian with FWHM equals to the seeing quality.

#### 4.6. Final data product

For every observed field we process all dithered spectral difference frames as described above to yield telluric corrected relatively flux calibrated, two-dimensional spectra. Then we co-add the 2D spectra of each target and extract one-dimensional spectra using either a double-box (“positive” and “negative” in order to work with the difference image) or optimal extraction with the double-Gaussian profile (also “positive” and “negative”) corresponding to the profile widths of alignment stars. The two-dimensional spectra from difference images are collapsed by inverting and offsetting a half of each spectrum and then adding it to another half.

The final data product is available in several formats: (a) multi-extension FITS file with one extension per 2D extracted calibrated co-added spectrum; (b) single-extension FITS file with all extracted 1D spectra; (c) a Euro3D-FITS file (Kissler-Patig et al. 2004) for 2D extracted spectra; (d) a Euro3D-FITS file for 1D extracted spectra; (e) a ESO3D-FITS file (Kümmel et al. 2012) for 2D extracted spectra; (f) a ESO3D-FITS file for 1D extracted spectra. The first two files are accompanied with files in the same format providing flux uncertainties, while this information is stored in the Euro3D-FITS and ESO3D formats. MMIRS MOS spectra in the Euro3D-FITS and ESO3D formats contain metadata making them Virtual Observatory compliant (Chilingarian et al. 2006) and easy to visualise in specialised tools (Chilingarian et al. 2008).

#### 4.7. An example of a fully reduced dataset

Here we provide an example of a fully reduced MOS dataset obtained in the *HK* spectral setup with 1 arcsec wide slits in December of 2011 with the 6.5 m Magellan Clay telescope. The slit mask was exposed for a total of 7h 20min over two nights. The program was targeting intermediate redshift star-forming galaxies and active galactic nuclei and the dataset was kindly provided for illustrative purposes by the program PIs, R. Leiton and E. Daddi.

In Fig 5 we display stacked 2D, sky subtracted, telluric corrected, rectified spectra linearized in wavelength, and a plot of an extracted 1D spectrum for one of the objects. Emission line detections are clearly visible in several slits. Residuals of the night sky *OH* emission lines are barely

visible demonstrating the high quality of sky subtraction by our data reduction pipeline.

### 5. QUALITY OF THE SKY SUBTRACTION

In order to assess the quality of the sky subtraction, we compute the histogram of counts (converted to electrons) on a raw single spectral frame binned by intensity. We then compute the standard deviations of counts in every intensity bin with  $3\sigma$  outlier rejection in order to remove the effects of uncorrected hot pixels and cosmic ray hits. If a bin in intensity is sufficiently narrow, the standard deviation of counts on a sky subtracted frame corresponding to the narrow range of intensities on a non sky subtracted frame will provide a diagnostics of the sky subtraction quality. This computation is repeated for a single spectral frame and a difference spectrum. The theoretical noise limit corresponds to the square root of intensity (Poisson limit) at intermediate and high count rates, and approaches the plateau set by the read-out noise at low count rates. For the case of a difference frame, the read-out noise plateau is higher by a factor of  $\sqrt{2}$ . In Fig. 6 we present the result of this computation for a typical MMIRS MOS observation with the exposure time of 300 sec.

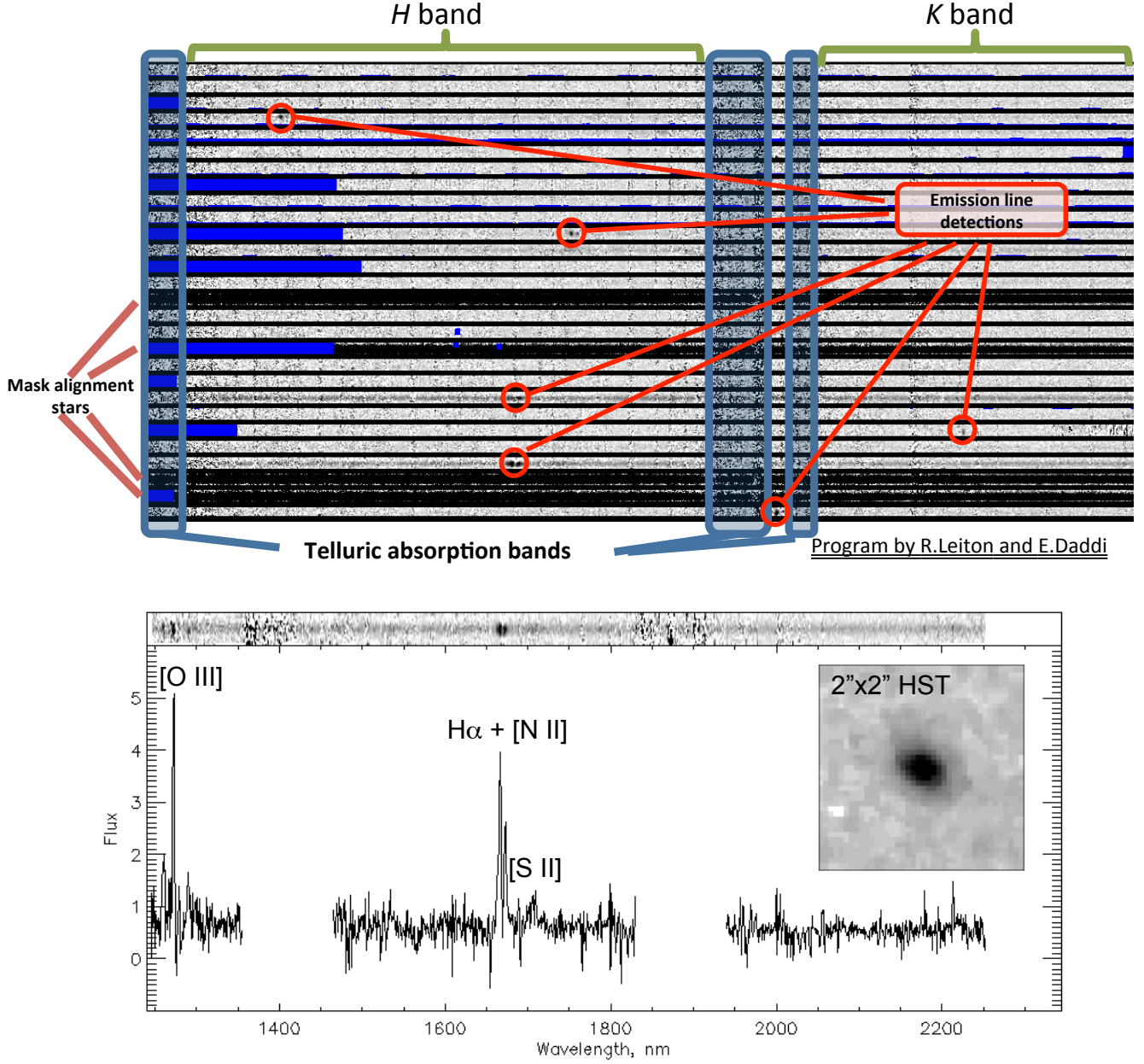
From this plot it is clear that our sky subtraction approach applied to difference spectra leaves residuals in *OH* lines consistent with the Poisson photon statistics.

However, when applied to single spectral exposures, it leaves significant residuals exceeding the Poisson limit by a factor of up-to 10. The main reason for this is probably the scattered light in the spectrograph, given that the pixel-to-pixel sensitivity variations of the HAWAII-2 detector are wavelength dependent. The dispersed light in the spectral traces on a detector plane is nearly monochromatic in every pixel, while the diffuse component of the scattered light is “white”. The diffuse component has the intensity of about 2%, while the pixel-to-pixel sensitivity variations reach 40% and a change by a factor of several as a function of wavelength. Therefore, on a single exposure, up-to 1% of the residual intensity will appear as noise, an increase of an order of magnitude in the uncertainties over the Poisson photon statistics. When dealing with difference spectra, on the other hand, the diffuse light modulated by pixel-to-pixel sensitivity variations almost completely cancels itself because of the subtraction. Hence, the sky model becomes representative of the residual *OH* lines and the sky subtraction becomes Poisson limited.

### 6. SUMMARY

We present a spectroscopic data reduction pipeline for the multi-object near-infrared spectrograph MMIRS capable of reducing large data volumes in an automatic way. We describe the observational protocol that should be followed by observers in order to make the data compatible with our pipeline.

We implement the pipeline as a stand-alone software package in IDL with minimal software dependencies. Our pipeline supports both the long-slit and multi-object spectroscopic modes. Pipeline execution is controlled by text parameter files with the format resembling that of FITS headers. The text files can be created manually, or generated using a script that accesses a relational database containing the observational metadata.



**Figure 5.** Fully reduced extracted 2D slits (top panel) and an extracted 1D spectrum (bottom panel) for a deep NIR spectroscopic dataset obtained with the 6.5 m Magellan Clay telescope in December of 2011. The inset in the bottom panel displays a  $2\times 2$  arcsec fragment of the Hubble Space Telescope image of a  $z = 1.54$  galaxy having the total Vega  $H$  band magnitude  $m_H = 19.8$  mag. The integration time was 7h 20min with the 0.6 arcsec average seeing quality.

We implement novel algorithms for sky subtraction and telluric correction. We demonstrate that our sky subtraction technique provides sky subtraction quality close to the Poisson limit set by the photon statistics. Our telluric correction technique requires only one telluric standard observation, and differentially adjusts the standard to the airmass of a corresponding science observation using a grid of synthetic atmosphere transmission models.

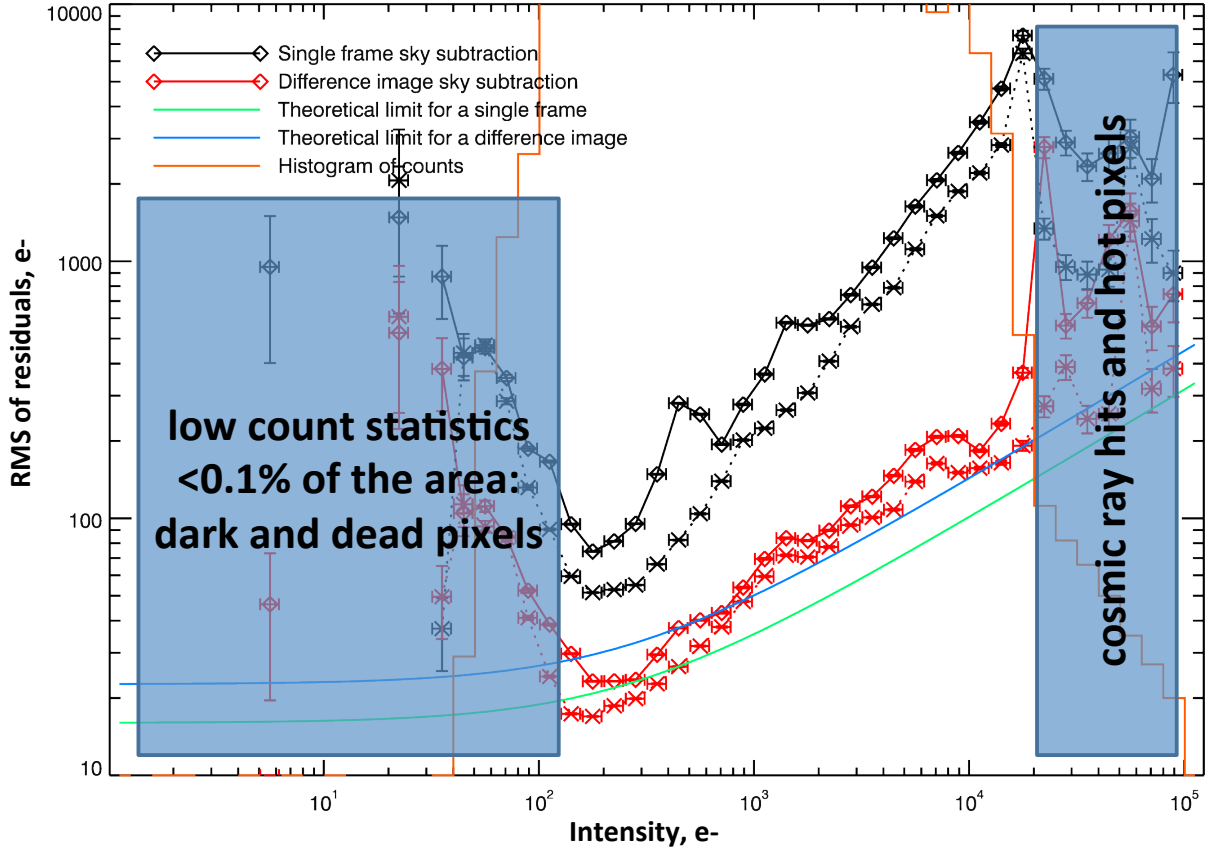
The pipeline can be used in real-time at a telescope to perform quick data reduction in order to assess data quality.

With minor modifications our pipeline can be adopted as a data reduction solution for other long-slit and multi-object optical and NIR spectrographs operated by dif-

ferent observatories. For example, we anticipate that this pipeline will become the workhorse data reduction pipeline for Binspec, a multi-slit optical spectrograph that will soon be commissioned on the MMT.

## 7. ACKNOWLEDGMENTS

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**Figure 6.** The assessment of the sky subtraction quality provided by the MMIRS pipeline for an observation using the *HK* grism with the pre-2014B version of the instrument equipped with the HAWAII-2 detector. The blue solid line corresponds to the theoretical sky subtraction quality limit from the Poisson photon statistics and read-out noise for a double correlated read. The solid red curve displays the measured variance of the sky residuals as a function of intensity. The dashed red curve presents the same measurements made using  $\sigma$ -clipping in the distributions of counts in order to eliminate the effects of residual cosmic ray hits and warm or cold pixels.

colleagues Jessica Mink and Andrew Szentgyorgyi for useful discussions. IC acknowledges the additional support from the Russian Science Foundation project 14-22-00041.

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## APPENDIX

## TECHNICAL DETAILS ABOUT THE PIPELINE CODE

*The pipeline calibration data*

The pipeline is distributed with a set of calibration data required for the proper functionality of the code located in the *calib\_MMIRS/* directory. They are organized in a set of sub-directories corresponding to their functional purposes.

The detector specific calibrations stored in the *calib\_MMIRS/H2\_56/* folder include the specific information for the HAWAII-2 detector serial number 56 that had been used in MMIRS in 2009-2014. There are two files presenting the detector layout for the read-out modes using 4 and 32 amplifiers. They have a format of the binary FITS table with one row per amplifier defining its minimal and maximal pixel coordinates in X and Y axes, and the read-out direction in the detector, “1” for the horizontal and “2” for the vertical directions respectively. The *nonlinearity/* sub-folder contains the definition of the correcting polynomial that needs to be applied to the raw counts in order to put them into the linear scale. It also contains the bias and saturation values. This information is provided per each row or column (depending on the read-out direction) for every amplifier. Hence, 4096 sets of values are given as the entries of the binary FITS table. Below we describe the algorithm of the derivation of the non-linearity correction.

The *calib\_MMIRS/LS/* and *calib\_MMIRS/MOS/* directories contain the template distortion maps for all grism/filter combinations in the longslit and MOS spectral configurations respectively. The longlist folder also contains the mask definition files (one for each slit width) describing the long slit layout in the format identical to that of the MOS masks. These files are replicated into the data reduction directories as “mask\_mos.txt” in order to use the same data reduction routines as those for the MOS mode without introducing any modifications to the code.

The *calib\_MMIRS/linelists/* folder contains lists of spectral lines with wavelengths and relative intensities used for the wavelength calibration of MMIRS spectra (see above). There are two lists, one containing argon lines from the arc line lamp, and another one with the OH lines when the wavelength solution is computed from the science frames themselves.

The information required to perform the telluric correction is stored in the *calib\_MMIRS/sky\_transmission/* and *calib\_MMIRS/telluric/* directories. The former folder contains the grid of atmosphere transmission models computed with the ATRAN code for the Gemini-South telescope and downloaded from the Gemini observatory web-site<sup>8</sup>. The latter directory contains high resolution ATLAS9 models (Castelli & Kurucz 2004; Kurucz 2005) of synthetic stellar atmospheres for the *A0V* and *G0V* spectral types corresponding to stars used as telluric standards during MMIRS spectroscopic observations. The Gemini-South telescope is geographically located relatively nearby (about 150 km) to the Las Campanas Observatory in Chile where one would expect similar atmosphere conditions, therefore we did not compute the specific atmosphere transmission models for LCO but simply used those provided by Gemini.

*Defining the non-linearity correction*

The non-linearity correction is a crucial step in the primary data reduction because NIR detectors are known to have a non-linear response at all intensity levels (Vacca et al. 2004). In addition to the non-linearity, the detector has a so-called reset effect, that is an additive constant signal level that appears after the detector reset (cleaning) procedure at the beginning of each exposure and then declines exponentially with time. A natural way to calibrate the non-linear response is to take a long up-the-ramp exposure of a constant source of light such as imaging flat field until the detector saturates. The intensity of the source, however, has to be relatively low to provide enough sampling of the response curve. Then, if the detector response is ideally linear, the counts will grow linearly in time until the saturation and any measured deviation from the linear behavior will be due to the detector response.

Since for practical reasons it is nearly impossible to have an absolute calibration of the flat field light source, we either have to deal with differential correcting functions or define a count range where the non-linearity is the lowest and cross-calibrate the bright and faint tails of the response curve to that region. We decided to use the latter option and found that the lowest non-linearity of the MMIRS HAWAII-2 detector is achieved between 5000 and 9000 counts above the bias level.

The internal flat field lamp in the imaging mode is too bright to obtain good sampling of the response curve, therefore we used science observations of stellar fields in different photometric bands that we found in the MMIRS archive. Thus, the night sky played a role of the constant light source. We manually chose exposures without extended sources and avoided crowded fields. The count rates (counts per second) from the night sky vary by two orders of magnitude in different filters (*Y* being the faintest and *H* being the brightest). This allowed us to sample well the detector response curve from very low fluxes (100 counts) up to the saturation levels (40000 counts).

We started with the *K*-band filter observations and defined the response curve at the 5000–10000 count range, then used *Y* and *J* band observations in the low end and *H* and *HK* band observations in the high end cross-calibrating them to the initial part of the curve. This operation was repeated for different up-the-ramp settings. Then, we performed the fitting of the response curve for every row/column in every read-out amplifier (see above the description of the amplifier layout).

<sup>8</sup> <http://www.gemini.edu/>

We fit the reset-effect by an exponential function and find an exponential decay timescale of 2.7 sec. Therefore, it has very little effect on the data obtained in the up-the-ramp settings with read-out cadence of 5 sec or longer. This additive effect is taken out during the primary reduction process separately from the non-linearity correction.

Then we fit the non-linear response curve in the 100–39000 count range by the 9th order polynomial function and obtained the RMS residuals of less than 2 counts in the whole range of intensities. The response of the detector is non-linear at a few per cent level under 3000 and above 15000 counts, however after applying the correction we reach a sub-per cent level of non-linearity.

#### *Obtaining the initial wavelength solution approximations*

A key to the efficient and precise wavelength calibration of MMIRS spectral data is the availability of high quality (to within a couple of pixels) initial approximation of the wavelength solution, sufficient for easy automatic identification of spectral lines. The initial approximations for all MMIRS grism settings are kept inside the pipeline code. Here we briefly describe how we obtain them in order to show how we will handle new grisms. This procedure must be done for every new grism installed in the instrument, but does not need to be performed again by pipeline users.

From longslit spectroscopic observations we measure the curvature of the slit image defining the average pixel shift of the wavelength solution with respect to the slit center. This offset is parametrized by the 3rd order polynomial of the Y coordinate that will also apply to MOS slit masks.

Then we manually identify a dozen arc lines in several MOS slits covering a large range of X slit mask positions, apply the offsets corresponding to the Y positions computed at the previous step, and then fit dispersion relations (i.e. wavelength as a function of pixel position on a detector plane) with low order one-dimensional polynomials. Finally, we fit the behavior of the zeroth and first order coefficients as a function of X slit mask positions. The approximate solutions are stored in the pipeline code.

#### *Dependencies and modified versions of third-party software used in the pipeline*

The current version of the pipeline relies on one third-party IDL package and a few routines extracted from their original packages and modified for our purposes. Here we briefly describe these routines and the ways they are used in the pipeline.

The only package that must be installed in the system before the pipeline can be used is the IDL Astronomy User's Library<sup>9</sup>, or ASTROLIB, distributed by NASA Goddard Space Flight Center. We use a number of routines from ASTROLIB to perform the input-output operations on FITS files and binary tables, IDL data structures, and also some routines to compute outlier resistant statistics on datasets.

Here we present a list of modified and/or extracted routines used in the pipeline.

- FIND\_1D.PRO, CNTRD\_1D.PRO, GCNTRD\_1D.PRO are modified versions of the corresponding routines from the IDLPHOT sub-package in ASTROLIB which were modified in order to operate on one-dimensional arrays (vectors in the IDL terminology) rather than on two-dimensional images
- SFIT\_2DEG.PRO is a rewritten version of the SFIT.PRO 2D surface fitting routine from the IDL distribution that allows one to use different degrees of the polynomial approximation on two spatial dimensions
- GOODPOLY\_ERR.PRO is a modified version of the GOODPOLY.PRO outlier resistant polynomial fitting routine by Marc Buie<sup>10</sup> that allows one to specify measurement errors
- LA\_COSMIC\_ARRAY.PRO is a modified version of the Laplacian cosmic ray filtering technique (van Dokkum 2001) that allows us to deal with data arrays instead of lists of input images and also has a keyword to reject negative outliers that is required to deal with difference spectral frames
- Extracted routines from SDSS IDLUTILS<sup>11</sup>: we use certain mathematical algorithms from the IDLUTILS package and their dependencies including the *b*-spline fitting routines. We also provide modified versions of the *b*-spline fitting code with the “\_3d” suffix that allow one to fit a *b*-spline approximation on a scattered dataset with two extra dimensions used in the MMIRS sky subtraction algorithm.

#### EXAMPLE OF A TASK CONTROL FILE

Here we provide an example of a MMIRS pipeline task control file generated automatically by a PERL script using a PostgreSQL database containing metadata of all MMIRS observations.

```
SIMPLE      =                               T / FITS-like header
LONGSTRN= 'OGIP 1.0'                       / The OGIP long string convention may be used.
RAW_DIR    = '/data/mmirs/Archive/rawdata/data/MMIRS/2011.1203/'
R_DIR      = '/d1/data1/mmirs/preproc/2011/2011.1203/'
W_DIR      = '/d1/data1/mmirs/reduced/2011/2011.1203/lei1.a1_mask1_HK_HK/01/'
RAWEXT     = '.gz'
```

<sup>9</sup> <http://idlastro.gsfc.nasa.gov/>

<sup>10</sup> <http://www.boulder.swri.edu/~buie/>

<sup>11</sup> <http://www.sdss3.org/dr8/software/idlutils.php>

```

INSTRUME= 'MMIRS' / spectrograph name
SLIT      = 'mos' / slit name or MOS
GRISM     = 'HK' / grism
FILTER    = 'HK' / filter
BRIGHT    = 0 / bright source 1=Yes 0=No
SCI       = 'lei1.a1_mos.8456' / science frame (only one)
SCI2      = 'lei1.a1_mos.8457' / second science frame (only one)
DITHPOS   = 1.8000 / current dithering position in arcsec
DITHPOS2= -1.4000 / dithering position for the second frame
DARKSCI   = 'dark.8653,dark.8654,dark.8655,dark.8656,dark.8657' / dark frame(s) for science
ARC       = 'comp_mos.8468' / arc frames
DARKARC   = 'dark.8638,dark.8639,dark.8640,dark.8641,dark.8642' / dark frame(s) for arc
FLAT      = 'flat_mos.8470'
DARKFLAT= 'dark.8628,dark.8629,dark.8630,dark.8631,dark.8632' / dark frame(s) for flat
STAR01    = 'HIP-16904_mos.8491,HIP-16904_mos.8492,HIP-16904_mos.8494,&'
CONTINUE  = 'HIP-16904_mos.8514,HIP-16904_mos.8516'
DARKST01= 'dark.8638,dark.8639,dark.8640,dark.8641,dark.8642'
STTYPE01= 'a0v'
STAR02    = 'HIP-16904_mos.8596,HIP-16904_mos.8597,HIP-16904_mos.8598,&'
CONTINUE  = 'HIP-16904_mos.8599,HIP-16904_mos.8600'
DARKST02= 'dark.8638,dark.8639,dark.8640,dark.8641,dark.8642'
STTYPE02= 'a0v'
COMMENT   flat fielding settings
FFSCFLAT= 0 / subtract scattered light from flat field?
FFSCSCI   = 0 / subtract scattered light from science frames?
FFNSLIT   = -1 / normalize to slit #N, -1 for per-slit normalization
COMMENT   wavelength calibration settings
WLNDEG    = 3 / polynomial degree along dispersion
WLYNDEG   = 3 / polynomial degree across dispersion
WLDEBUG   = 0 / debug setting
WLPLLOT   = 0 / plot the arc line identification spectrum on the screen
WLADJ     = 1 / adjust wavelength solution using all slits
WLOH      = 1 / use OH lines to build the wavelength solution
SKIPLINE= ' ' / arc lines NOT to use
COMMENT   sky subtraction settings
SSADJWL   = 1 / use the adjusted wavelength solution?
SSDIM     = 3 / 3-dimension or 2-dimension sky model?
SSDEBUG   = 0 / debug for sky subtraction
COMMENT   linearisation settings
LINADJWL= 1 / use the adjusted wavelength solution?
LINSSBOX= 1 / sky subtraction in linearized spectra in all "BOX" slits
LINSSTRG= 1 / sky subtraction in linearized spectra in all "TARGET" slits
COMMENT   extraction settings
EXTMETH   = 1 / 1 - box extraction, 2 - optimal extraction
EXTAPW    = 5 / extraction aperture in pixels, window with or gaussian FWHM
EXTDFBOX= 0 / use alignbox star positions to get empirical dithering offset?
EXTBOXEX= 'obj-sky' / image type to use alignbox positions from
COMMENT   process the following reduction steps (yes=1/no=0)
S01PROC   = 1 / up-the-ramp fitting (if needed) and dark subtraction
S02PROC   = 1 / distortion map creation
S03PROC   = 1 / flat-fielding and 2D slit extraction
S04PROC   = 1 / wavelength calibration
S05PROC   = 1 / sky subtraction
S06PROC   = 1 / linearisation
S07PROC   = 1 / extraction
S08PROC   = 1 / telluric star processing
S09PROC   = 0 / telluric correction
COMMENT   create_task.pl -m lei1.a1 -t mask1 -g HK -f HK -d lei1_HK_HK/ -s HIP%
END

```